# Structure and Seismicity of the Wabash Valley Seismic Zone

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Gary L. Pavlis, Michael W. Hamburger, Kevin Eagar, and Jiedi Wu
Department of Geological Sciences, Indiana University,Bloomington IN 47405
(pavlis@indiana.edu , hamburg@indiana.edu, jiwu@indiana.edu )

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## Introduction

In the past decade our understanding of earthquake hazards in southern Indiana has been profoundly changed through results from paloeseismology studies. Hundreds of liquefaction features that are believed to be the result of local earthquake ground motion were systematically surveyed and examined by Obermeier *et al.* (1991, 1992) and Munson *et al.* (1993, 1994) along river banks and exposures of late Pleistocene and Holocene sediments. This evidence indicates the lower Wabash Valley area has experienced repeated earthquakes with magnitude of 6.7 or larger during Holocene times. The historical and instrumental records also show that although the seismicity rate is much lower than a typical plate boundary region, activity is by no means zero. Nuttli's (1979) historical records show that numerous felt events occurred in this region prior to modern network recording. In the combined historical and instrumental record at least seven events with than $m_b \geq 5$ have occurred in the region (Nuttli, 1979, 1983; Taylor et al., 1989; Kim, 2003).

In spite of the clear evidence that the Wabash Valley Seismic Zone (WVSZ) represents a significant seismic risk, the area has not received a level of seismic monitoring consistent with the threat. While the New Madrid region has been heavily instrumented with station densities higher than most of California, the WVSZ has consistently remained at the fringe of the national seismic monitoring infrastructure. This has limited the quality and quantity of data available to appraise seismic risk in the region. In this project we are addressing this problem by using two underutilized, seismic data sets that provide new constraints on this problem.

1. We are analyzing data acquired by the Indiana PEPP educational seismic network (Figure 1). The PEPP network (Hamburger and Pavlis, 2003; see http://www.indiana.edu/~pepp) began as an education and outreach effort as part of the national seismology education and outreach program called the Princeton Earth Physics Project (PEPP). PEPP's original goal was to link science teachers and university groups doing seismology research to form a national network of seismic stations operated in schools. We have held regular workshop with teachers at participating schools since 1996 to form a strong working collaboration with teachers in 22 schools with 28 active teachers. An important element of this project is utilizing the data these teachers have helped us collect for a useful scientific purpose. Until now the primary purpose of the network was educational. Support from this project is helping us extend the research objectives of the PEPP network and provide an important focus for high school students and teachers involved in the network.

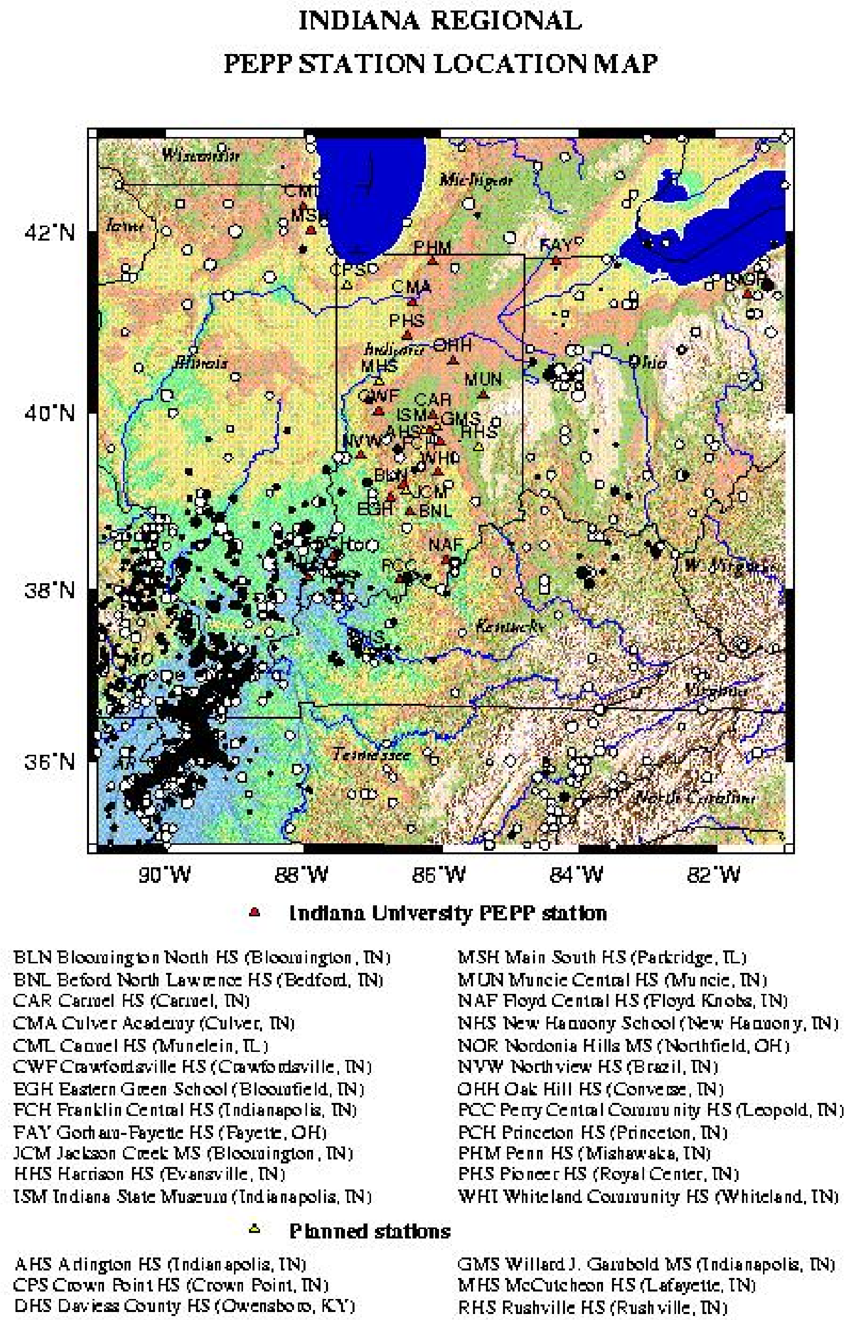


**Figure 1.** Stations of the Indiana PEPP network.

2. We used data from a temporary network of seismic stations deployed in 1995-1996 as part of a collaborative experiment focused on detecting and locating small earthquakes within the WVSZ (Figure 2). The results provided new constraints on seismic hazards in theWVSZ (Pavlis et al., 2002), but as in most experimental programs

there were numerous research questions that justified further work on these data.

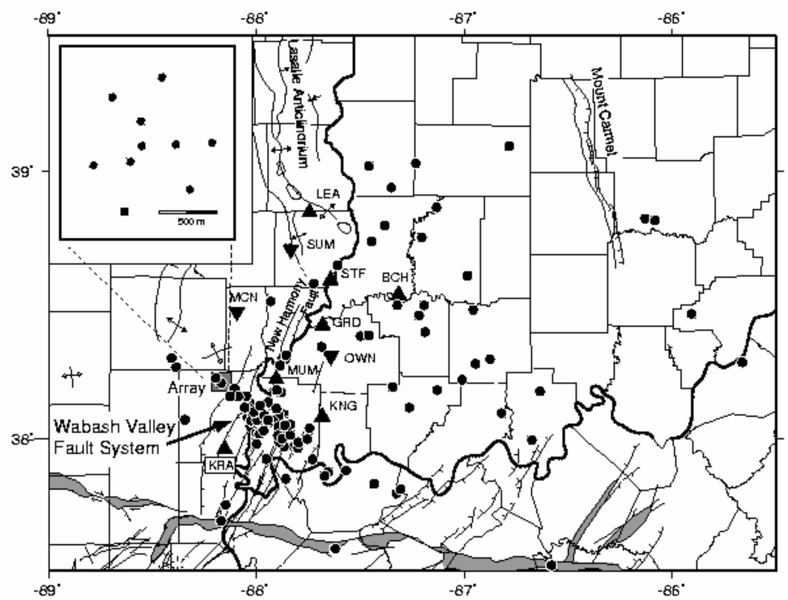


**Figure 2**. Seismicity results of 1995-1996 Wabash Valley experiment (from Pavlis et al., 2002). Circles are events identified as earthquakes. Triangles show the location seismic stations that operated in triggered mode. (Inverted triangles used geophone strings for noise reduction instead of single sensors.). The inset square shows the geometry of a phased array deployed in southeastern Illinois (location shown by shaded square).

This report summarizes the results of four projects completed or in progress on these data: (1) teleseismic P wave tomography for the Illinios Basin region; (2) a detailed analysis of microearthquakes in the "New Harmony cluster" in southwestern Indiana (Figure 2); (3) performance analysis of the PEPP network; and (4) an educational research collaboration analyzing mining and quarry explosions in the southern Illinois Basin. These projects define individual sections in the remainder of this report.

**Teleseismic P-wave Tomography**

Wu (2004) recently completed the first ever tomographic inversion of the lower crust and upper mantle beneath the Illinois Basin. She utilized data from teleseismic earthquakes recorded by the PEPP network (Figure 1) and from the MOMA experiment (Fouch et al., 2000). Key results of this work are:

1. The data suggest that seismic velocities the upper mantle in central Indiana are slightly higher than that to the southeast and north (Figure 3). Because the lower velocities correlate with the Illinois and Michigan basins, respectively, and the higher velocities correlate with the basement arch between them, Wu (2004) suggested that these regional-scale geologic structures could have been controlled by variations in upper mantle strength.

2. Analysis of near-surface velocities indicates a relatively low-velocity uppermost mantle beneath the seismically active part of the WVSZ (-XX% relative to neighboring areas of Indiana and Illinois)
3. A detailed analysis of the resolution of this tomographic model (Wu, 2004) indicates that both the magnitude of the velocity variations and the vertical location of the variations seen in Figure 3 are poorly constrained. With the existing data set, we can, however, document a systematic difference in average lithospheric properties between central Indiana and the neighboring basins.

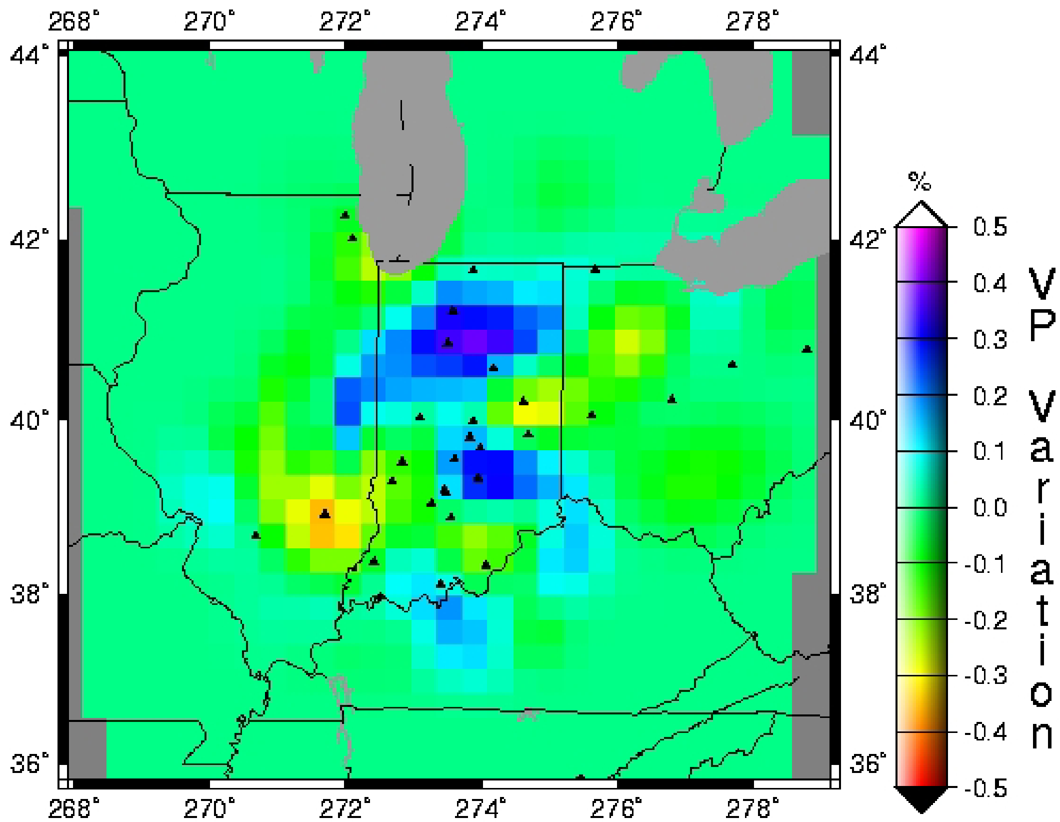


**Figure 3.** P wave tomography result for a depth slice at 180 km from Wu (2004). Stations are shown as black triangles on this map. Colors show P velocity variations as a percentage perturbation from the initial layer velocity.

## Analysis of the New Harmony Cluster

We undertook a focused study of an unusual feature in the seismicity of the Wabash Valley seismic zone that we will refer to as the New Harmony Cluster (Pavlis et al., 2002). This feature was discovered during data processing of the 1995-1996 Wabash Valley experiment. It is defined by the cluster of events near the Wabash River between the stations KRA and MUM (Figure 2). Pavlis et al. (2002) noted that the events in that cluster showed a remarkable similarity in waveforms. Because of this observation they argued that the New Harmony Cluster was probably much smaller in size than Figure 2 would suggest and the scatter in those locations was due mainly to location errors. We aimed to test this hypothesis and obtain more insight on this feature through a focused study of these events. In order to examine these events, we have completed an exhaustive data processing effort, including: (1) retrieval of all array data from our archive and reformatting into a unified database; (2) array processing of the data for an additional 109 days of network operation using the same procedures described in the Pavlis et al. (2002) paper: array processing of the continuous data from the phased array to produce semblance versus time plots; running a specialized detector we developed to identify potential events; and running an interactive array processing procedure to measure P and S wave slowness vectors and construct array beam signals for all three components of the array. During interactive processing we skipped events that were clear mining explosions; (3) merging the array beam data with data from the triggered stations (Figure 2); and (4) locating these events using the dbgenloc program (Pavlis et al., 2004).

The new catalog for the experiment produced by this procedure produced a new catalog with a total of 657 events that were identified as possible earthquakes. The overall catalog shows a similar spatial pattern to that shown in Figure 2. There is a large concentration of events in the New Harmony cluster and a fairly random distribution of events elsewhere. To test the hypothesis that most of the events were tightly clustered we separated events of the New Harmony Cluster from the rest of the catalog. To do this we scanned all the array beam records for signals that had the shape we had previously learned to recognize as diagnostic of this cluster. We identified 537 events by this procedure, mostly recorded only on the phased array only. We found only 8 waveforms with observable signals on any of the triggered stations. This observation underscores the value of the phased array in studying low-level seismicity associated with intraplate seismic zones.

To improve the consistency of P and S picks from the array beam traces we utilized a cross-correlation method with results illustrated in Figure 4. We selected the event with the largest amplitude as a master trace for cross-correlation and used a time-domain method to align all traces to the nearest sample. Figure 4 compares signal alignment based on the original, hand-picked data with the results after cross-correlation. This figure demonstrates the remarkable similarity of waveforms and the success of the correlation procedure for P waves. The results for the S phase using the horizontal components were good, but somewhat less consistent due to the lower signal-to-noise ratio that characterized the horizontal component data.

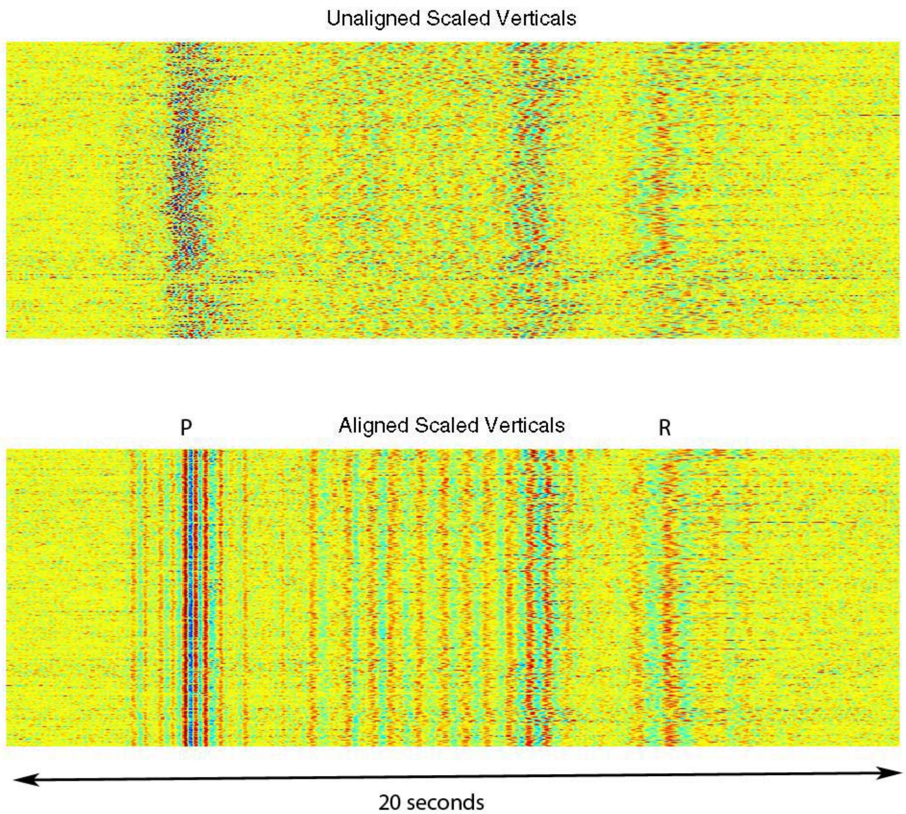


**Figure 4.** Result of cross correlation analysis of events for vertical-beam traces using events in the New Harmony cluster. Waveforms of 537 events identified with this cluster are shown here in two image displays. The time axis for each seismogram runs from left to right using time relative to a measured P wave arrival time. Each seismogram is displayed with a color map scaled to the peak amplitude of each trace and stacked from top to bottom. The top image shows the data aligned on the hand-picked P times, while the bottom shows the same data aligned by cross-correlation. The improvement in alignment of the P phase (series of red and blue bands to the left side of the figure) is clear. There significant residual variation in the R phase (right side of display) suggesting a variation in R-P time of the order of approximately 1 s, which translates to an epicentral distance range of no more than about 3 km.

The revised picks were used to relocate the events from the New Harmony Cluster with the results shown in Figure 5. Significant scatter still remains in these data due to two factors we are currently working to improve:

1. Figure 5 used all P and S cross-correlation results directly with only a minimal check to throw out gross outliers. Because of ambiguity in identifying initial S-wave arrivals, a number of the revised S picks could easily be wrong by several seconds. Our current working hypothesis is that the north-south bands of seismicity seen in Figure 5 are an artifact of 'cycle skips' in S and/or P cross-correlation results. We are currently working to refine these measurements and expect that most of the scatter in the east-west direction will disappear when we correct these problems.
2. Some of the S phase slowness vector measurements are grossly in error. This causes some of these events to be located in an incorrect direction from the array. This is an artifact caused by the fact that almost all of these locations are determined only from the phased array data. When P and S beams define grossly

different propagation azimuths the location procedure, which seeks to minimize a weighted L2 norm of time and slowness residuals (Pavlis et al., 2004), finds a solution with an azimuth between the two beam directions. When the S azimuth is drastically in error, this leads to a solution that is grossly wrong. This problem may be improved by simply discarding S slowness vector data when the measured azimuth is inconsistent with the azimuth determined from the P phase.

Work to correct these problems is underway. We anticipate that the final relocation will produce a dense concentration of events distributed roughly parallel to the Wabash River and near the town of New Harmony. We note that the north-south scatter is almost certainly a data limitation that we will not be able to get around. The north-south location precision is almost completely controlled by the array beam azimuth uncertainty. This is limited by the data bandwidth to a few degrees. When we have a clearer picture of the absolute location of this cluster of events we plan to consult records of the Indiana and Illinois geological surveys related to oil and coal mine locations. This will allow us to evaluate the hypothesis raised by Pavlis et al. (2002) that these events may be induced by oil and gas production or coal mining.

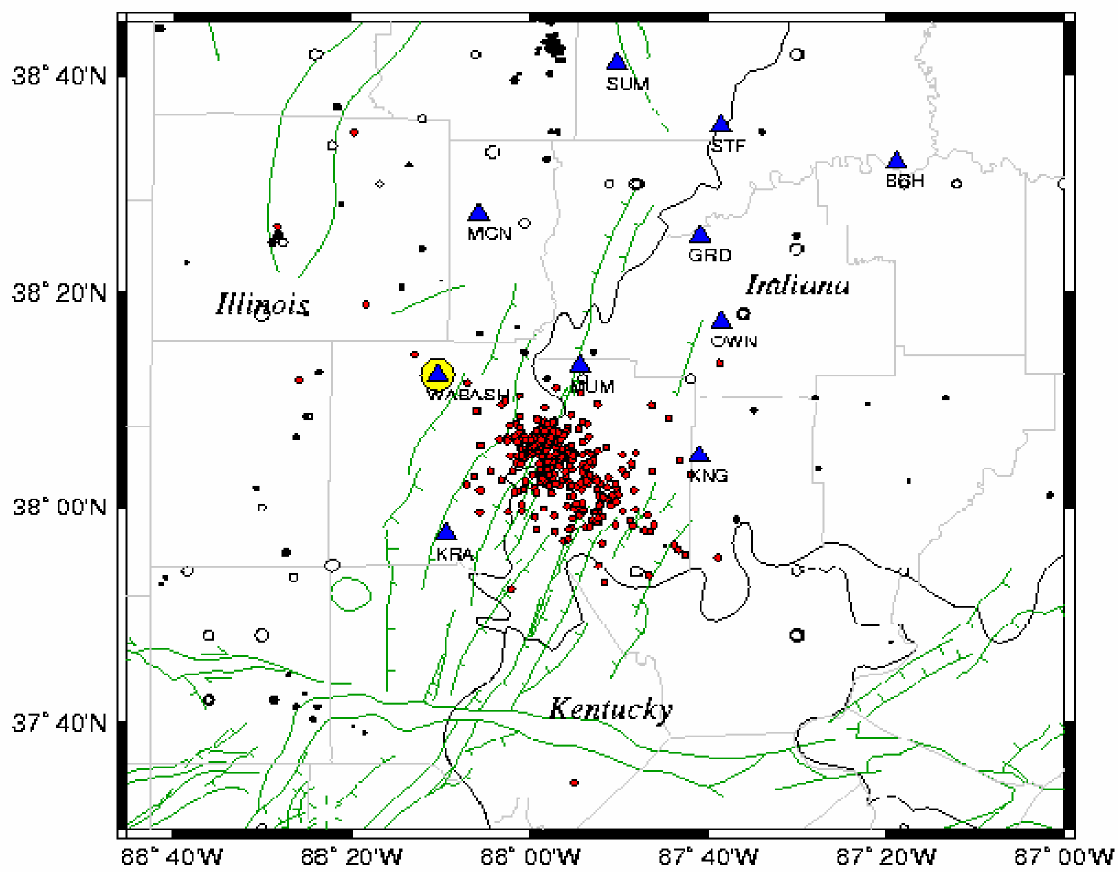


**Figure 5.** New Harmony Cluster event locations. Blue triangles are seismic stations from the 1995-1996 Wabash Valley experiment. The triangle with the yellow circle is the location of the phased array that provided the primary constraint on these events. Red dots are current location estimates of events in the New Harmony cluster and black dots are location estimates of events from the regional (SLU) catalog.

State and county outlines for this region in southwestern Indiana are shown. Green lines show the location of mapped faults.

## PEPP Network Detection Analysis

We have undertaken a careful scan of data from the PEPP network (Figure 1). We concluded this was necessary as attempts to utilize detections from the real-time system showed serious problems. The primary reason for this is that a large fraction of events detected by this network are mining explosions from coal and aggregate mines. Significant numbers of events were clearly being missed due to the fact that signals generated by mining explosions in this region are commonly dominated totally by Rayleigh waves in the 0.5 to 2 Hz band. Because these signals propagate at a low velocity compared to P and S (group velocity near 2 km/s), detectors tuned to P and S moveout times do not work well. We scanned 143 days of data from 2002 with the event counts shown in Figure 6. The total event count comes to approximately 27 events per day. As this figure shows most of the events are clear explosions. The broadband sensors in this network are detecting approximately 12 teleseismic events per week. The 161 events listed in Figure 6 as “Unknown” are in that category because the standard explosion discriminant that we use (large-amplitude surface waves and small body wave phases) is ambiguous for those events. We are currently in the process of examining that group of events more carefully to separate that segment of the event population into “earthquakes” and “probable explosions”. Visual scans of these data done in preparing this report suggest that there are probably less than 10 clear earthquakes in this time period.

We expect to combine the event counts from this analysis with the results of our reanalysis of the 1995-1996 experiment to produce new data on recurrence rates for this region.

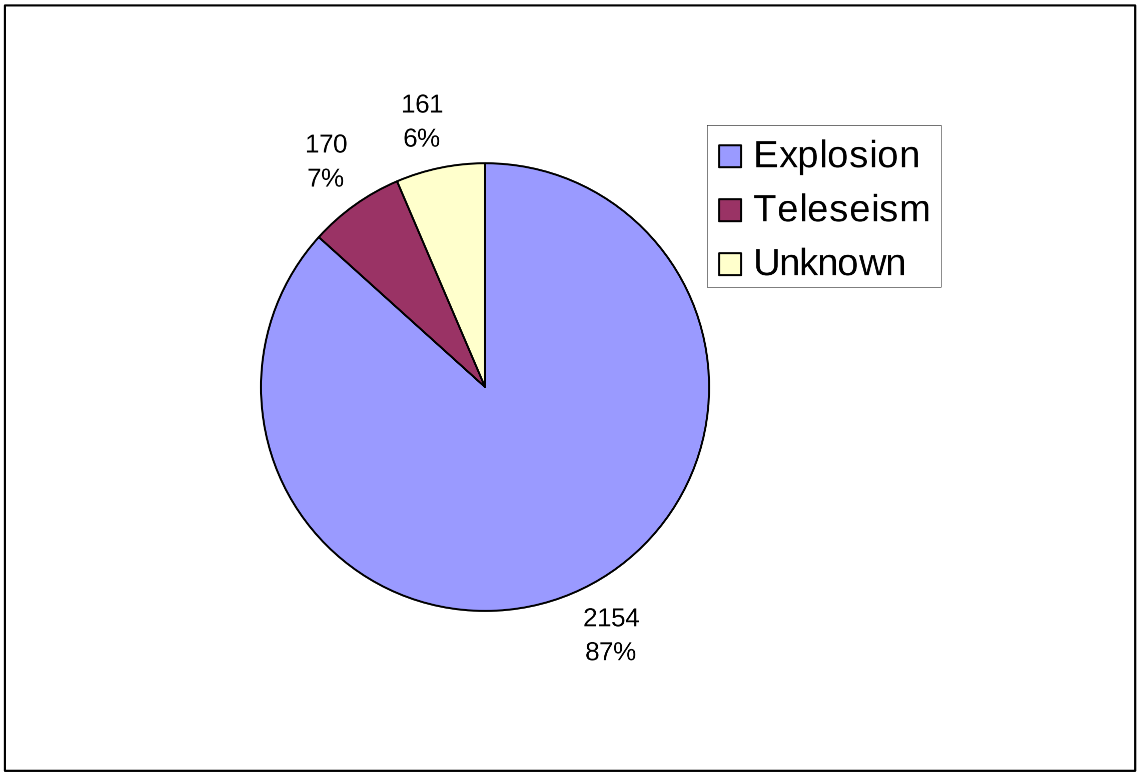


**Figure 6.** Event counts for 143 days of data from 2002. This is a pie chart showing numbers of events of different types detected by manually scanning these data for signals. Thus these figures show the maximum number of events that could be detected, although not necessarily located, with the PEPPSI network. Note that the total event count is approximately 27 events per day.

## Education and Outreach

A unique aspect of the PEPP network is that it is not just a network of seismic instrumentation but also a network of science and education professionals interested in seismology education and outreach. Over the past 8 years we have established a strong collegial relationship with one or two teachers in each of the schools shown in Figure 1. A very important element of this project is that it provides a research focus for our teacher partners. To retain their interest and the interest of their students it is important that they see these data being used for scientific research. Our work on this project has helped greatly in this way. In addition, we have two ongoing programs that enhance the educational impact of this project.

1. For the past 5 years we have been running a special program aimed at top middle and high school science students we call the IU-PEPP Earthquake Science Symposium. This program aims to provide these students a research experience with state-of-the-art seismic data. Teachers act as research advisors and mentors to small groups of students. The students attend a fall and/or spring research symposium. The fall symposium stresses training, while the spring symposium is more aimed at student presentations on independent research project. (see http://www.indiana.edu/~pepp/workshops/2003_04student/SpringPictures.htm)

2. With support from this project we invited three teachers to work with us this past summer as 'PEPP Research Fellows'. The main objective of this program was to provide these teachers some real-life research experience in seismology that would improve their ability to teach science in general and earthquake science in particular. For this reason the projects they undertook were focused on problems they could readily transport to working with students. Since most of the seismic events we see are explosions (Figure 6) all three elected to work with explosion data. Two of them (Michael Kelley [Harrison HS, Evansville, IN] and William Combs [Crawfordsville HS, Crawfordsville, IN]) worked with travel-time data from a set of mining explosions with known locations. The locations had been obtained in earlier student projects and through direct on-site measurements by Kelley. They produce a useful set of travel time curves for P, S, and Rg phases measured in a set of narrow frequency bands. The third teacher, Ewa Shannon (Crown Point HS, Crown Point, IN), worked with amplitude data from the same set of ground-truth explosions. She developed empirically determined amplitude decay curves for Rg that she used to develop a 'pseudomagnitude' scale based on Rg (it remains a 'pseudomagnitude' as we do not yet have an independent calibration method to equivalence these to a local or regional magnitude scale). She compared pseudomagnitude estimates to known blasting parameters (total shot size, shots per hole, and shot size per hole) and found poor correlation between the pseudomagnitude and any of these parameters. She concluded that local blasting practice and differences in local site characteristics had a larger effect than any of the tabulated blasting parameter. The conclusion is consistent with similar results from nuclear monitoring research directed at discrimination of chemical explosions. The scientific results of this experiment, as well as results from other PEPP Fellows' work, were presented at the Fall AGU meeting in San Francisco (Combs et al, 2004; Sayers, 2004; Pavlis and Hamburger, 2004).

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